Impact of Duration Thresholds on Atlantic Tropical Cyclone Counts

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May 7th, 2009
Re-submitted to JClimate

Abstract

Records of Atlantic basin tropical cyclones (TCs) since the late-19th Century indicate a very large upward trend in storm frequency. This increase in documented TCs has been previously interpreted as resulting from anthropogenic climate change. However, improvements in observing and recording practices provide an alternative interpretation for these changes: recent studies suggest that the number of potentially missed TCs is sufficient to explain a large part of the recorded increase in TC counts. This study explores the influence of another factor--TC duration--on observed changes in TC frequency, using a widely-used Atlantic TC database: HURDAT. We find that the occurrence of short-lived storms (duration two days or less) in the database has increased dramatically, from less than one per year in the late-19th/early-20th Century to about five per year since about 2000, while moderate to long-lived storms have increased little, if at all. Thus, the previously documented increase in total TC frequency since the late 19th Century in the database is primarily due to an increase in very short-lived TCs.

We also undertake a sampling study based upon the distribution of ship observations, which provides quantitative estimates of the frequency of "missed" TCs, focusing just on the moderate- to long-lived systems with durations exceeding two days. Both in the raw HURDAT database, and upon adding the estimated numbers of missed TCs, the time series of moderate to long-lived Atlantic TCs show substantial multi-decadal variability, but neither time series exhibits a significant trend since the late-19th Century, with a nominal decrease in the adjusted time series.

Thus, to understand the source of the century-scale increase in Atlantic TC counts in HURDAT, one must explain the relatively monotonic increase in very short duration

storms since the late-19th Century. While it is possible that the recorded increase in short duration TCs represents a real climate signal, we consider it is more plausible that the increase arises primarily from improvements in the quantity and quality of observations, along with enhanced interpretation techniques, which have allowed National Hurricane Center forecasters to better monitor and detect initial TC formation, and thus incorporate increasing numbers of very short-lived systems into the TC database.

1. **Introduction:**

Increases in tropical cyclone (TC – here referring only to those with maximum sustained surface winds of at least 18 ms^{-1} including subtropical cyclones[1]) activity due to anthropogenic climate change, would be of concern given the massive societal disruptions and potential for large numbers of fatalities that these oceanic phenomena can cause upon landfall in heavily populated coastal communities (IWTC 2007). While possible changes of TC intensity, frequency, duration, track, rainfall, and storm surge must all be considered, in this report our focus is on past records of TC frequency in the Atlantic basin.

From a climate modeling perspective, most studies have focused on future projections of TC activity, limiting their direct utility for comparison with past observed trends. An exception is Bengtsson et al. (2007) who find no significant trend in Atlantic TCs in a 20th century radiative forcing hindcast experiment. Concerning future projections, existing climate model and regional downscaling studies yield mixed projections of the influence of a substantial 21st century greenhouse warming on Atlantic basin (including the North Atlantic Ocean, Caribbean Sea, and Gulf of Mexico) TC frequency. Some studies suggest modest frequency increases of 15-35% (Oouchi et al. 2006, Chauvin et al. 2006), some indicate little to no change in numbers (Bengtsson et al. 2007, Emanuel et al. 2008), while others predict even a modest decrease in frequency by 15-30% (McDonald et al. 2005, Chauvin et al. 2006, Knutson et al. 2008, Gualdi et al. 2008). In some cases (Chauvin et al., 2005 and Emanuel et al., 2008) where multiple climate models were examined using a single downscaling model, the sign of the projected change in TC frequency was seen to

[1] As discussed in Neumann et al. (1999) and Landsea et al. (2008), while the formal designation of subtropical cyclones began in 1968, such systems were likely included within HURDAT earlier but considered to be tropical cyclones. Without routine satellite imagery to discern the convective structure, differentiating true tropical cyclones from subtropical cyclones is nearly impossible.

depend on the particular climate model chosen to provide the large-scale climate change projection. The lack of large modeled increase in TC frequency in the Atlantic in response to CO_2–induced warming may be due to the combination of dynamical changes (e.g., increases in tropospheric vertical wind shear) and changes in the thermodynamic state, which offset the increases in SST (e.g., Vecchi and Soden 2007a; 2007b).

Observational studies similarly report a wide range of conclusions on the long-term frequency changes in Atlantic TCs. Two studies (Mann and Emanuel 2006, Holland and Webster 2007), using unadjusted HURDAT data, concluded that a rather dramatic – at least 100% - increase in TC frequency occurred during the last century (see Figure 1) that they attributed to SST warming caused by anthropogenic climate change. Both studies made the explicit assumption that the database was complete or nearly so for TC frequency. Documentation accompanying the HURDAT database (Landsea et al 2004) had earlier estimated that up to four TCs per year were "missed" near the beginning of the 20th Century because of lack of observational networks over the open Atlantic Ocean. The number of "missed" TCs was later estimated by comparing the ratio of landfalling TCs versus total number of systems in the pre-geostationary satellite era (before 1966) versus the current era (Landsea 2007). The ratio showed a large step-function drop at 1966, which, it was argued, suggests that about two TCs per year were missed from about 1900 (the first year when nearly all landfalling TCs would likely have been monitored) until 1965, although Holland (2007) questions the hypothesis that the proportion of storms making landfall remains stationary. Mann et al. (2007a) demonstrated that even with the Landsea (2007) adjustment to the TC record there is observed a large and unprecedented increase in TC frequency during the last decade.

Mann et al. (2007b) estimated the frequency of unsampled Atlantic TCs by fitting the TC frequency record against environmental factors thought to be relevant to variability of TC frequency. They related year-to-year seasonal TC numbers to Atlantic sea surface temperatures, the El Nino-Southern Oscillation, and the North Atlantic Oscillation for the period of 1944 to 2006 and then applied the relationship obtained to the period 1870 to 1943 in the pre-aircraft reconnaissance era to then estimate how many TCs were missed on average yearly. Their results indicated an undercount exists of about 1.2 TCs per year (with a likely range of 0.5 to 2.0) for 1870 to 1943. However, the study assumed that the physical link between the century-scale trend in Atlantic SSTs and the trend in the Atlantic TC counts can be adequately described by their statistical model. Given that the recent dynamical modeling studies of anthropogenic climate change (described earlier) and other statistical methods (Swanson 2008, Vecchi et al. 2008) suggest only relatively small sensitivity of Atlantic TC frequency to a relatively uniform tropical SST increase, as is projected in typical greenhouse warming scenarios, the authors' underlying assumption may not be physically valid. It should be noted that regional scale SST changes on the interannual and multidecadal timescale appear quite important for TC frequency variations (e.g., Kossin et al. 2007), but there is considerable evidence (e.g., Knutson et al. 2008; Vecchi et al. 2008) that the more uniform tropical SST trends, as projected by climate models for increasing greenhouse gases, will affect Atlantic TC frequency quite differently.

An alternative analysis approach has been used (Chang and Guo 2007, Vecchi and Knutson 2008 – henceforth VK08) to quantify the time change in the number of "missing" Atlantic TCs based upon the density of ship observations during the last century. Both studies suggested that a significant upward trend remains in the counts of TCs when starting from about 1900, although VK08 found that the trend from 1878 onward was not significant. An assumption common to both the Chang and Guo (2007) and VK08 analyses is that any TC observable in the International Comprehensive Ocean-Atmosphere Data Set (ICOADS – Worley et al. [2005]) ship data would have already been included into the Atlantic hurricane database (HURDAT[2] – Jarvinen et al. 1984). The ICOADS ship database was recently incorporated into the reanalyses that have been completed for 1911 to 1925 (Landsea et al. 2008), and was the primary tool in helping to identify 23 additional TCs for those years; there were also two TCs removed from HURDAT because they did not meet today's TC criteria. Unfortunately, ICOADS has not yet been utilized for the reassessment of HURDAT for the period of 1851 to 1910 (Landsea et al. 2004) nor for the years of 1926 onward. Thus, based upon the results obtained thus far with the TC reanalyses incorporating ICOADS, we speculate that about one additional TC per year for the late 19th and early 20th Century will eventually need to be added to the numbers of "missing" TCs estimated earlier (Chang and Guo 2007, VK08).

Landsea (2007) argued that in the last several years, roughly one additional TC per year had been identified and included into HURDAT because of new tools and techniques such as Quikscat satellite imagery (Atlas et al. 2001), the Advanced Microwave Sounding Unit (Bruske and Velden 2003), and the Cyclone Phase Space Analyses (Hart 2003). These methods have allowed for the detection of very short-lived systems that might not have been analyzed as having gale force winds previously as well as more accurate

[2] ICOADS contains raw ship-based observations including ship position, wind speed and direction, air and sea temperatures, and sea level pressures. HURDAT, in contrast, is a database of analyzed TC positions and intensities (estimated maximum sustained surface wind speeds and central pressures) every 6 hours. The original HURDAT certainly utilized whatever ship observations were available operationally, but ICOADS typically provides significantly more ship data for reassessing existing TCs and for discovering previously undocumented TCs.

differentiation of cyclones that were better characterized as TCs rather than primarily baroclinic, extratropical cyclones[3]. If one is better able to observe systems over the tropical and subtropical oceans through enhanced monitoring networks, then these changes could contribute toward more TCs (especially very short-lived ones) being accurately indentified and thus included into HURDAT[4]. However, this additional one TC per year during the last several years has not been well-quantified nor objectively determined (Landsea 2007).

In 2007, the Atlantic hurricane season was notable for the very large number of very short-lived (and typically weak) TCs that were named and included into HURDAT (Knabb et al. 2009). Out of the 15 total, nine TCs were identified that lasted for 2.0 days or less at tropical storm force intensity, compared to an average of about two very short-lived TCs per year during the 20th Century. There was also a substantial number – four – of very short-lived, weak TCs in 2008 (Brown et al. 2009). These observations are suggestive that the number of additional very short-lived TCs introduced in recent years is larger than that estimated earlier in Landsea (2007).

Each of these studies has aimed to improve our understanding of historical Atlantic TC activity by estimating the number of "missed" TCs, but it is evident that we will never know with certainty how many real storms were not detected, and each of the proposed corrections can be open to criticism. Some of the methods (e.g., Landsea 2007; Mann et al. 2007b) assume *a priori* that certain characteristics of TCs have remained stationary over

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[3] It is possible that there have been some cyclones included as tropical/subtropical storms in HURDAT in the past that would not have been included in recent years because of technological advances which, if they had been available in the past, would have indicated that the storms did not have TC intensity and/or structure. However, it is likely that the increase in TC counts due to improved observing capabilities is much larger than the number of non-tropical storms misclassified as TCs in the past due to limited observing and analysis capabilities.

[4] It is important to note that very short-lived TCs do not significantly contribute toward overall activity in a TC basin using indices such as the Accumulated Cyclone Energy (ACE) index (e.g., Bell et al. 2000) and Power Dissipation Index (PDI) (e.g., Emanuel 2005, Swanson 2007), which are designed to measure the combined impact of TC frequency, intensity, and duration.

the period of analysis, though these assumptions can be open to question. As noted by VK08 (p. 3599), "…while…we estimate certain key sources of uncertainty in the historical Atlantic TC database, other possible sources of uncertainty remain…. Thus, our current estimates of long-term changes in TC activity should be regarded as tentative, particularly when analyses span periods in which substantial changes in observing practices have occurred, and efforts should continue to update and enhance our historical records of TCs and their uncertainties".

Our goal in this paper is to expand our understanding of the character of the historical record of Atlantic TCs, by examining the century scale trend behavior of TCs of different duration classes. First, an analysis of the time series for very short-lived TCs is conducted to show how this class of storms contributes to the trend in the whole TC database. Then, the methodology of VK08 is employed for the TC database (but with the very short-lived systems removed) to examine how many medium to long-lived TCs have been unsampled in earlier years and how this impacts trends from the resulting time series. Finally, we offer our interpretation of the results in the Summary and Discussion section, including a discussion of the impact of duration thresholds on TC counts within a coupled climate modeling framework.

2. **Observational Results**

2.a. **The observational record of very short-lived tropical cyclones.**

Figure 2 shows the frequency of very short-lived TCs (total duration of 2.0 days or less at tropical storm or hurricane force throughout the TCs lifetime[5]) back to 1878, the first year

[5] A wide range of duration thresholds for very short-lived TCs was tested and can be found in the on-line supplement. The conclusions presented here are insensitive to the exact threshold chosen.

that the U.S. Army Signal Corp began systematically attempting to trace all West Indian hurricanes (Fernández-Partagás and Diaz, 1996). The frequency of these events increased dramatically during the last century. From the late 1870s until about 1940, there was an average of about one very short-lived TC per year. During the 1940s until about 1960, the frequency increased roughly coincident with the advent of aircraft reconnaissance and satellite imagery (see Figure 6 of Sheets 1990). The frequency remained relatively constant at about three per year from around 1960 until about 2000. Another step-like increase appears to have occurred in the last several years, corresponding to further improvements in TC analysis and monitoring (see Discussion Section). Spatially, these very short-lived TCs have a similar distribution throughout the Atlantic basin as the whole HURDAT dataset (not shown).

The increase in short-duration storm counts in HURDAT, which can be seen clearly in Figure 2, is statistically significant by a variety of measures. The positive linear least-squares trend in short-duration TCs over 1878-2008 (2.79 storms per century) is both large (almost twice as large as the mean over the full period, 1.57) and significantly different from zero at $p < 0.01$, using a Students-t test and estimating the degrees of freedom from the lag-1 autocorrelation of the detrended timeseries (see VK08 or Santer et al. 2000 for a description of the test). We also compute an alternative measure of secular change, the median of pair-wise slopes (MPWS; Lanzante 1996); this non-parametric test of secular change is robust to outliers and has an influence function that is constant over the entire time series. The 1878-2008 MPWS of short-duration storms is significantly different from zero at $p < 0.01$, using a Spearman's rank test. We use linear trends and medians of pairwise slopes in this paper as statistical measures of secular change, not as a "best fit" to the observed data. As noted by VK08 (see their Fig. 11), the GFDL CM2.0 and 2.1 climate model runs suggest that the response of tropical Atlantic SSTs to anthropogenic forcing over the past 140 years has been a quasi-linear warming, which supports our use of a linear trend test in the present analysis.

The results in Tables 1 and 2 show that the statistical significance of the different measures of secular change in short-storm counts is robust, whether the statistics are computed over the period 1878-2008, 1900-2008 or 1903-1994 (the latter using two negative Atlantic Multidecadal Oscillation periods as endpoints – Zhang and Delworth 2006). The amplitude of the linear trend and MPWS is also relatively unchanged by choosing the three different intervals, indicating that the increase in the counts of short-duration TCs on the century time-scale is relatively monotonic. Thus, the long-term increase in short-duration TCs in HURDAT is a robust and significant feature of the database.

2.b. **The long-term trend of moderate to long-lived tropical cyclone frequency.**

Removing very short-lived TCs from the entire database (Figure 3) reveals a substantially reduced long-term trend during the last century in the remaining "moderate- to long-lived" TCs, but interannual and multi-decadal variability is relatively unchanged. The moderate- to long-lived TCs series shows a significant upward trend when starting from 1900, but not from 1878, nor between 1903-1994 (see Table 1). The median of pairwise slopes of moderate- to long-lived TCs is not statistically significant over 1878-2008 ($p = 0.24$) or over 1903-1994 ($p = 0.76$), while it is significant over the period 1900-2008 ($p = 0.02$ - Table 2). The statistical significance of the century-scale change in moderate- to long-duration storms appears to depend strongly on choosing a date near 1900 as a starting point and a date near 2005 as an end point.

The moderate- to long-duration TC record is still impacted by the complication of how many TCs (of, in this case, greater than 2.0 day lifetime) were not sampled because of sparser shipping traffic over the open Atlantic Ocean in earlier decades of the record (Chang and Guo 2007, VK08). Therefore, we apply the methodology of VK08*,* which allows for a quantitative estimate of the number of "missed" TCs that have occurred over the Atlantic, using only the satellite-era storms of duration larger than two days to estimate missing storm rates (Figure 4). About three missed moderate- to long-lived TCs are estimated for the 1880s, dropping to two per year in the 1900s, and down to less than one per year in the 1950s. Of note are the spikes of missed TCs in the 1910s and 1940s, corresponding to reduced ship observations available in ICOADS during the World War I and World War II (Worley et al. 2005). Figure 4 also indicates that the estimated number of missed moderate- to long-lived TCs is reduced, by a small amount, compared with the total frequency of missed TCs of any duration estimated in VK08. This reduction in missing storms occurs in our new analysis because the very short-lived storms from the satellite era are no longer included in the sample of storm tracks that are tested for "encounters" with the historical ship tracks, so they cannot contribute to the missing storm estimate.

This estimated series of missed moderate- to long-lived TCs is added to the HURDAT time series of moderate- to long-lived TCs to obtain the adjusted time series (Figure 5). This series shows no significant (at p =0.05) linear trend nor MPWS, when calculated from either 1878 or 1900 onward (see Tables 1 and 2). The notion of no strong upward trend in Atlantic basin tropical storms is consistent also with the slight negative trends in U.S. landfalling tropical storm and hurricane counts since the late 1800s (e.g., VK08). Analyses presented in the on-line supplement and condensed in Figure 6 demonstrate that there has been an upward trend in very short-lived TCs during the 20th Century for durations of up to about three days with longer-lived TCs showing no significant trend. After inclusion of the estimated number of missed TCs, there remains no significant trend in the medium-to-long lived TCs once the duration threshold for retaining TCs reaches only 1.0 days. Thus the conclusions obtained from our statistical significance tests are quite robust to the choice of duration threshold.

3. **Summary and Discussion:**

The main findings from this paper include the following:

i) It was shown – for the first time – that there exists a large trend in the reported frequency of very short-lived Atlantic TCs, from less than one per year in the late 1800s and early 1900s to about five per year in the first few years of the 21st Century.

ii) Removal of the very short-lived TCs from the full TC frequency record results in a time series of medium to long-lived TCs that shows a substantially reduced – but still increasing – trend from the late 1800s to the early 2000s. Linear trends from 1878 to 2008 indicate a strongly significant increase from about 7 TCs per year in 1878 to about 12 per year in 2008 for the full TC dataset, but an insignificant increase from 7 to 8 TCs per year for the medium and long-lived TCs.

iii) Application of the VK08 sampling methodology allows us to estimate the number of "missed" TCs, specifically of medium and long-lived duration, due to limited reporting ship traffic in the pre-satellite era. This method suggests that about two TCs of medium to long duration were uncounted in the late 1800s, about one per year the first few decades of the 20th Century (with spikes during World Wars I and II), and less than one per year in the 1950s.

iv) Examination of the adjusted time series of medium-long lived TCs with our estimated number of "missed" TCs included indicates that no significant trend remains using either an 1878 or a 1900 starting point.

According to our analysis, the increasing trend in total Atlantic TCs since the late 19th and early 20th Centuries as documented previously by Mann and Emanuel (2006) and Holland and Webster (2007) can be re-described as primarily due to to a trend in very short-lived TCs, even before inclusion of likely unsampled TCs (Tables 1 and 2). Thus, the dramatic increase in very short-lived TC frequency in the database bears explanation.

We are unaware of a natural climate variability or anthropogenic climate change signal that should impact only very short-lived TCs, but - should one be found - that would be an explanation for the results shown here. An alternative explanation is that the increase in short-duration storms in HURDAT is an artifact of changing observing practices. Given the documented deficiencies in the historical record, it is entirely plausible that some of the increase in very short-lived TCs could have resulted from changes in observational systems and/or analysis techniques[6]. Several recent, very short-lived systems present anecdotal evidence in support of the idea that some TCs now being included into the Atlantic hurricane database may not have been "counted" previously. Their inclusion is in part due to enhanced technology (such as QuikSCAT) to newly observe tropical storm force winds

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[6] These issues are also mirrored by those examining trends in tornado frequency (Brooks and Dotzek, 2008), which also have seen a large jump primarily in weak tornadoes due to more enhanced observational networks including the Weather Surveillance Radar-88 Doppler (WSR-88D) radars.

as well as new analysis techniques (such as the Cyclone Phase Space diagrams) to better distinguish very short-lived TCs from very short-lived baroclinic systems.

For example, Figure 7 depicts very short-lived, weak (averaging only 20.6 m/s maximum intensity) systems in the last two seasons that we believe likely would not have been considered TCs previously (along with the specific new technology that facilitated their "naming" and inclusion into HURDAT): Andrea (2007 – Global Positioning System dropwindsondes – Hock and Franklin, 1999), Chantal (2007 – Quikscat), Jerry (2007 – Quikscat, Advanced Microwave Sounding Unit, and the Cyclone Phase Space), Melissa (2007 – Advanced Dvorak – Olander and Velden, 2007), Arthur (2008 – new moored buoy measurements, installed May 2005), and Nana (2008 – Advanced Scatterometer [ASCAT] – Verhoef and Stoffelen, 2009) . It is not disputed that these systems were indeed TCs and deserved to be included into HURDAT. On the contrary, NHC's increased ability to monitor even weak, very short-lived TCs means a better service to mariners in providing warnings of gale force winds and high seas. The inclusions of systems like these may be partially responsible for the apparent jump in the frequency of short-lived TCs that may have occurred around 2000 (as shown in section 2a). Given the temporal character of the increases in the number of very short-lived TCs seen in Figure 2 and their highly suggestive temporal relation with known technological improvements, we argue that the large increases in their frequency are most likely not depicting true climate changes[7]. Examination of the maximum intensities in the HURDAT database from 1878 to 2008 indicates that the very short-lived systems reached an average of just 25.4 m/s (tropical

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[7] The rather large increase in short-lived TCs in the last decade may be influencing the climatological average number of TCs in the Atlantic basin. Blake et al. (2007) utilized the years from 1966 to present as best representing the climatology of about 11 TCs per year, as this corresponds with the period of geostationary satellite surveillance. With the jump in the 2000s in the frequency of short-lived TCs, a more realisitc estimate of the long-term climatology may be closer to 13 TCs per year.

storm intensity), while the longer-lived TCs achieved an average of 40.2 m/s (upper end Category 1 hurricane intensity). This indicates that the increase in short-lived TCs has preferentially been through weaker TCs and that the TC frequency and intensity variability issues are not independent of one another.

Whatever the cause for the sizable increase in very short-lived TC numbers, the trends in very short-lived TCs and moderate to long-duration TCs are clearly substantially different in the HURDAT database. A possible contributor to the difference in short and medium- to long-lived storm trends is that some storms in the early part of the record that might have been classified as medium- to long-lived storms even though they were actually "short-lived". Such misclassification could have occurred due to observational limitations (e.g. intermittent periods during which a storm was not a true tropical storm but was not being adequately observed at the time, or a case where two separate systems might have been mistakenly identified as a single long-lived system in HURDAT). These errors could also partially account for the apparent increased frequency of short-lived TCs in the HURDAT database in recent years. If so, an adjustment for these errors would decrease the trend in short-lived storms and increase the trend in medium- to long-lived storms making the trends more similar between duration classes. Using our estimate for possible missing storms, we find no significant century-scale increases in the numbers of moderate to long-lived TCs (as measured by either a linear trend or by a median of pair-wise slopes). As discussed by VK08 and in this report, there are a number of remaining sources of error in our estimate of missing TCs – some of which would increase and some which would decrease long-term trend estimates. In our judgment, it is likely that our storm count adjustment is somewhat conservative overall, in that most of the assumptions utilized – a particularly important one being that all of the TCs to be found in ICOADS are already in HURDAT – would lead to even more missing TCs being estimated in the earlier decades and would act to further reinforce the lack of upward trends. Global warming simulations from high resolution global climate models and techniques that downscale coarser models to the regional scale are consistent with the findings of no increasing trend in the adjusted TC frequency records.

In addition to the influence on historical estimates of secular TC frequency change, there exists a very large sensitivity in TC frequency from coupled climate models to the duration threshold utilized to "count" a vortex seen in the simulation as a TC. In a recent study of global climate model simulations of the current climate and an enhanced greenhouse gases climate state (Bengtsson et al., 2007), various minimum thresholds for the parameters of intensity (in their study, this was quantified by lower tropospheric vorticity), baroclinicity (i.e., lower minus upper tropospheric vorticity), and duration of existence were explored in order to "count" a vortex as a TC. Bengtsson et al (2007) found, for example, by tightening the criterion of vorticity in doubling what was required that the number of vorticies counted as TCs was reduced from 105 down to 62 globally in their T213 experiment. Thus, in a global climate model, there is a large dependence of the TC counts on the intensity threshold chosen.

The sensitivity of various minimum duration thresholds from their T213 experiments was not elaborated upon in Bengtsson et al. (2007). Further analyses from these runs shows that in relaxing the duration threshold from 24 hr to 12 hr leads to a 68% increase in frequency globally for the late 20th Century climate (102 per year up to 171 per year) and in tightening the duration threshold from 24 hr to 48 hr leads to a 39% decrease in frequency (102 down to 62). In contrast, for a given duration threshold the change in frequency between late 20th Century and late 21st Century (with substantial greenhouse gas warming) displays only a 5-10% decrease in frequency in the latter time period. These modeling results lead us to speculate that TC counts in the real world are more sensitive to changes in observational monitoring ability for very short-lived TCs than to the influence of global warming. At the very least, comparisons between model and observed TC counts are influenced by the duration threshold chosen for the model TC definition, and efforts should be made to adopt consistent criteria.

In contrast to TC frequency findings reported here, several recent relatively high-resolution modeling studies suggest that the strongest TCs will become more numerous, despite some of them exhibiting reduced overall frequency of TCs—owing to increased intensities of the strongest storms (e.g., Knutson and Tuleya 2004, Bengtsson et al 2007, Emanuel et al 2008, Knutson et al. 2008). Given that TCs can be considered to be a Carnot heat engine to a first approximation (Emanuel 1987), TC intensity theory suggests that increasing sea surface temperatures and boundary layer moisture due to anthropogenic climate change could increase the potential intensity of TCs. Elsner et al. (2008) report that over the period 1981-2006 the intensities of the strongest TCs increased globally, though the signal they identified was most robust in the Atlantic basin, where multi-decadal variability in TC activity appears rather large and probably dominates trend calculations performed on relatively short time scales (e.g., since the 1980s). The issue of the temporal behavior of more intense TCs, such as major hurricanes, has not been addressed in this report. Since our ability to observe the maximum intensities of TCs has changed substantially over time, we anticipate severe difficulties in constructing reliable century-long records of these phenomena directly,

With impacts documented here and elsewhere of how limited ship-based observational sampling (and possibly increased technology) dramatically affects TC frequency over time, other aspects of TCs may likewise have observational biases within HURDAT. In particular, frequency of hurricanes and major hurricanes, duration of TCs, length of season, peak intensity, and integrated TC measures (like ACE and PDI) should not be used directly from HURDAT for climate variability and change studies without consideration of, or quantitatively accounting for, how observational network alterations are affecting these statistics. In general, subsampling of TCs back in time will artificially introduce increases in all of these parameters with time. In some cases, progress is being made (e.g., Elsner et al. 2008) at constructing more homogeneous satellite-based records to address these issues, at least for the period since 1981. The currently available 21st century projections of higher intensity TCs suggest that it would be advisable to increase efforts to reconstruct past time series (historical or pre-historic) of intense TC occurrence both in the Atlantic and the remaining global TC basins and to better monitor cyclone intensity and size in coming years, for example with a next-generation Quikscat satellite, improved sensors on manned reconnaissance, and unmanned aerial systems.

Acknowledgements

CWL acknowledges support of the NOAA Climate and Global Change Program through a grant on “A Re-analysis and Testing of Trends of Tropical Cyclone Data during the Aircraft Reconnaissance and Satellite Era”. GAV acknowledges support from the

NOAA/OAR C2D2. Useful comments were provided on earlier versions of this manuscript by Fabrice Chauvin, Kerry Emanuel, James Franklin, Colin McAdie, Ed Rappaport, Bill Read and three anonymous reviewers.

On-line Supplement:

As discussed in the main text of this manuscript, a large part of the secular increase in Atlantic cyclones recorded in HURDAT since the late-19th Century is due to an increase in very short-lived storms. Auxiliary Figure 1 shows the contribution to the 1878-2008 linear trend in Atlantic storm counts from storms of varying durations. In both the raw HURDAT data and that adjusted using the estimate of missed storms of Vecchi and Knutson [2008, VK08], the linear trend of storms in very short-lived categories – less than or equal to 2 days – provide the bulk of the increasing linear trend in storm counts. Meanwhile, there is a decrease in the number of longer-lived storms (duration > 7.5 days). It is unknown what the cause is for the decreased frequency of very long-lived TCs over this 130 year period.

In the main text, we used a two-day duration threshold for very short-lived storms, though this choice is somewhat arbitrary. However, as Figures A2-A17 show, the principal results discussed in the text (that the recorded increase in Atlantic storms since the late-19th Century is due to very short-lived storms, and that once these storms are removed there is no significant secular trend in Atlantic storm counts since the late-19th Century) are unaltered for a very short-lived storm threshold of 1.5 days and higher. As the threshold for very short-lived storm is increased, the adjustment of *VK08* is reduced, indicating that storms of greater duration were more easily detectable by the methodology of *VK08*.

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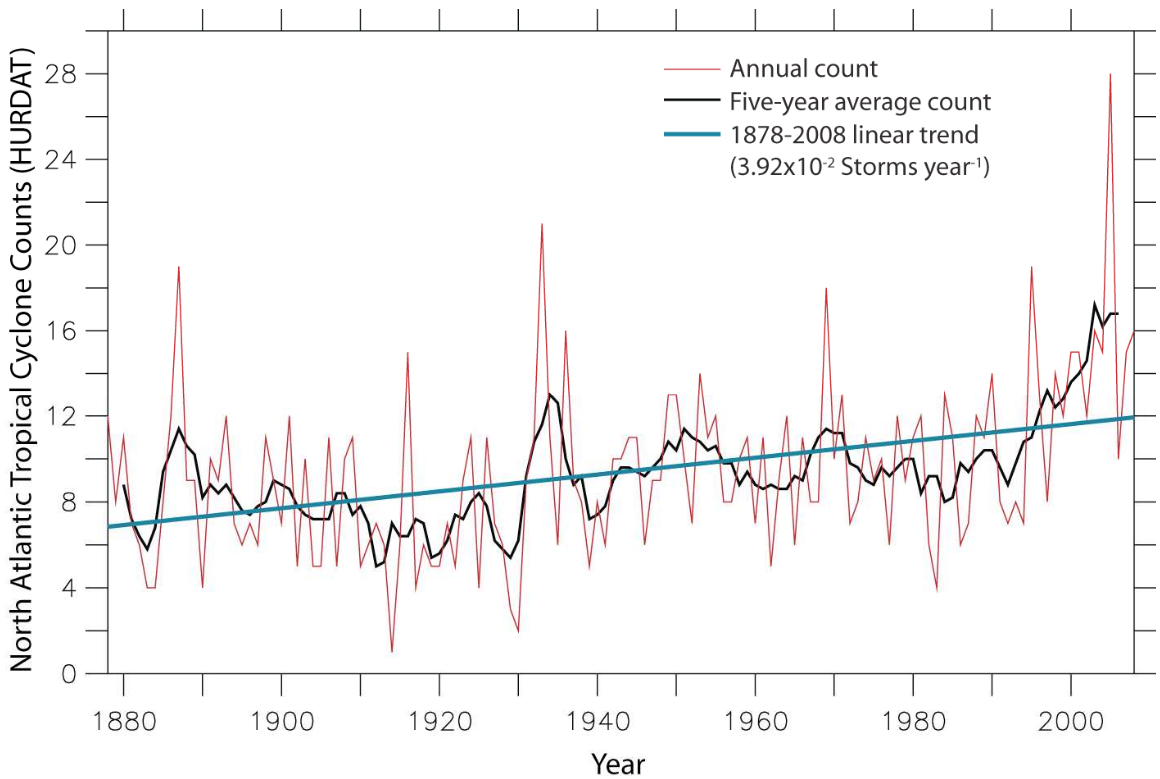

Figure 1: Frequency of all unadjusted Atlantic tropical cyclones (tropical and subtropical storms) from 1878 to 2008 (in red). The black curve is a five year centered mean and the blue line is the 1878 to 2008 trend.

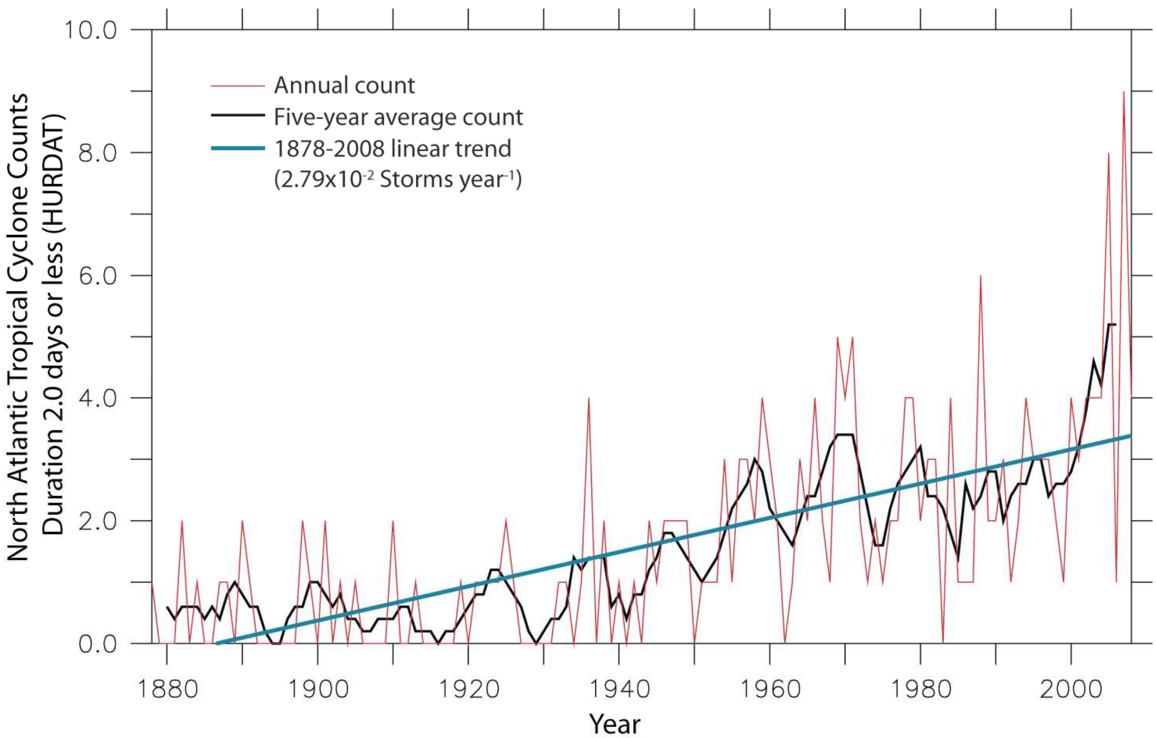

Figure 2: Frequency (in red) of all Atlantic very short-lived tropical cyclones (tropical and subtropical storms) which lasted as a gale-force tropical cyclone for 2.0 days or less from 1878 to 2008. The black curve is a five year centered mean and the blue line is the 1878 to 2008 trend.

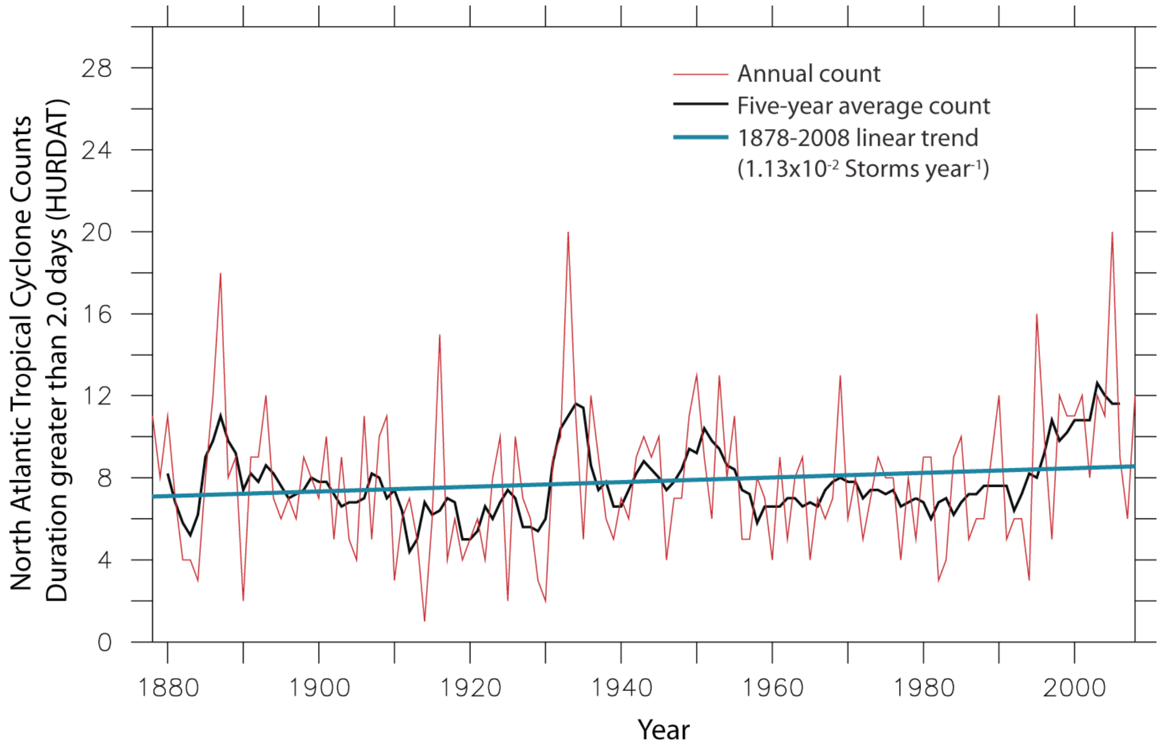

Figure 3: Frequency (in red) of "moderate to long-lived" Atlantic tropical cyclones from 1878 to 2008. The black curve is a five year centered mean and the blue line is the 1878 to 2008 trend.

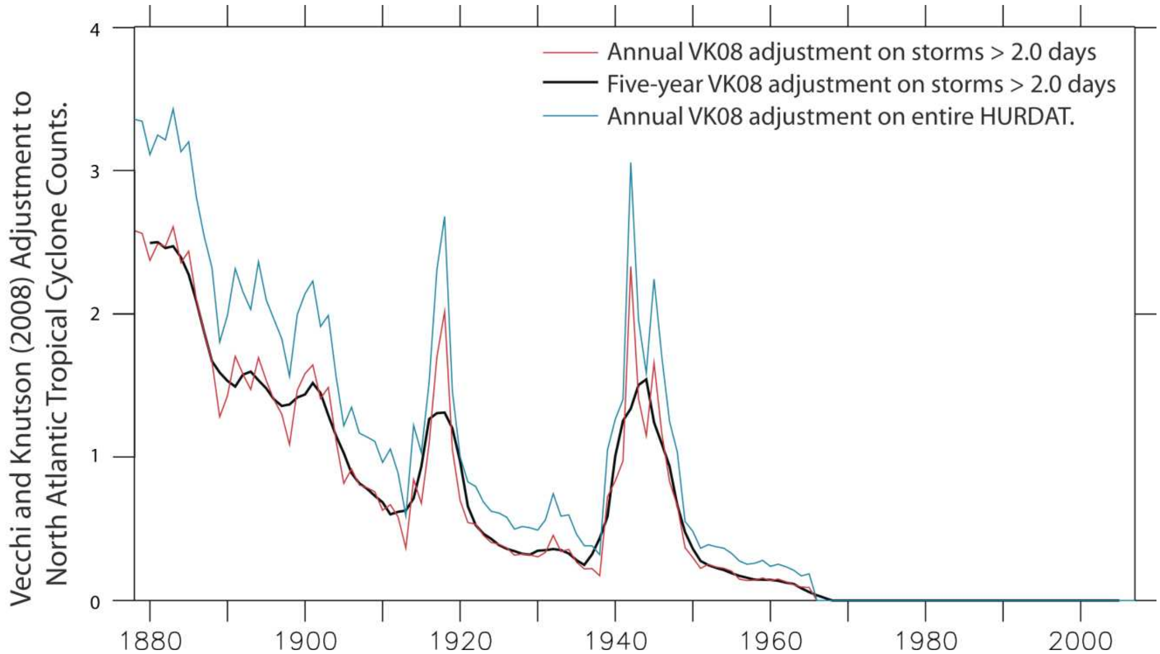

Figure 4: Estimated frequency (in red) of "missed" tropical cyclones of medium to long duration (greater than 2.0 days). The black curve is a five year centered mean. The blue curve is the estimated frequency of "missed" tropical cyclones of any duration. "Missed" storms estimated using the methodology of *VK08*.

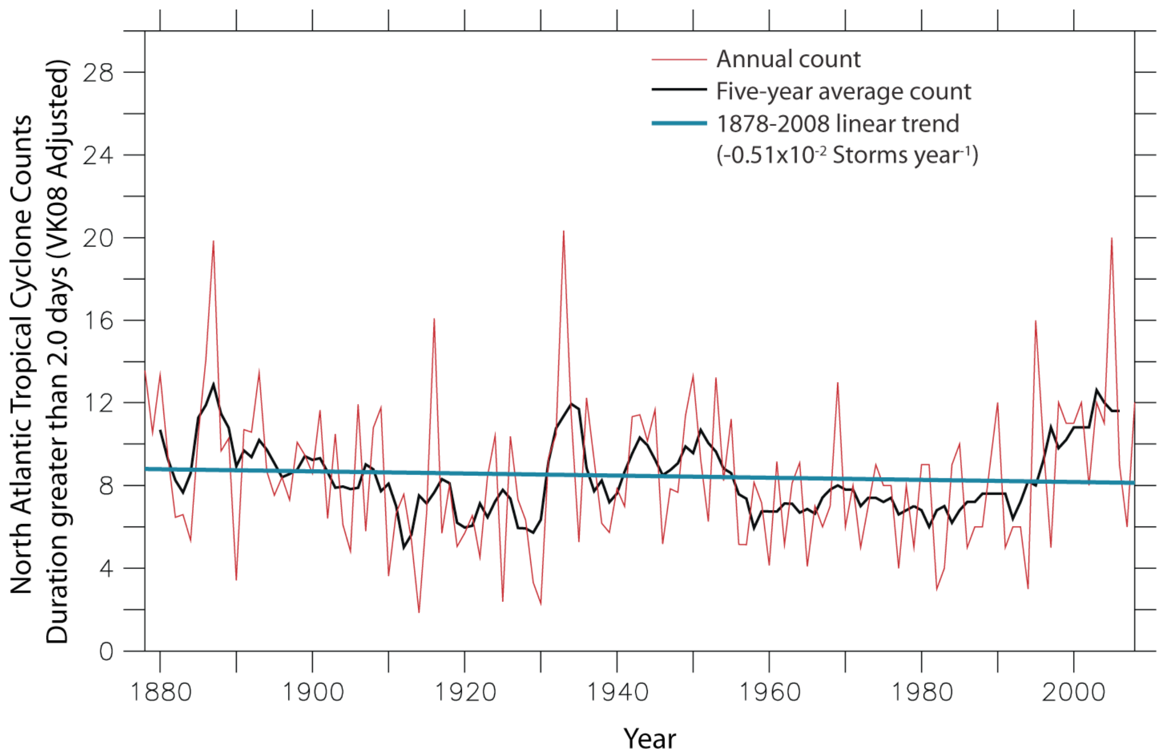

Figure 5: Adjusted frequency (in red) of Atlantic moderate to long-lived tropical cyclones from 1878 to 2008. The black curve is a five-year centered mean and the blue line is the 1878 to 2008 trend.

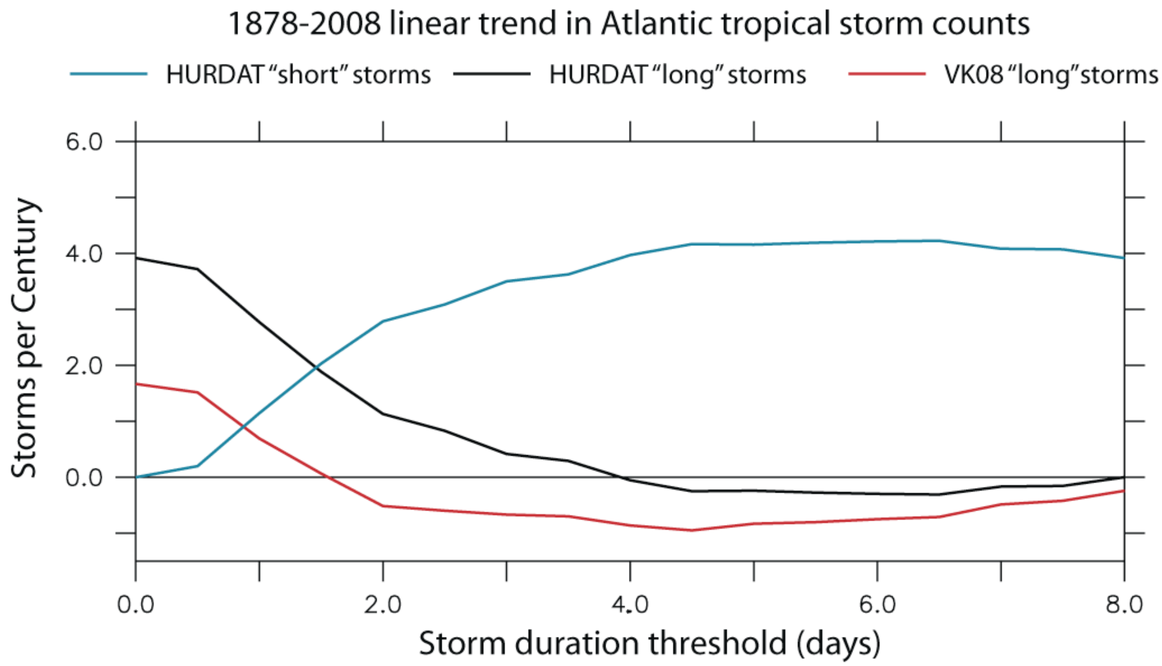

Figure 6: Comparison of long-term trends as a function of various thresholds of tropical cyclone duration for the period of 1878 to 2008. Blue indicates trend values for frequency of "short-lived" tropical cyclones of various durations. Black indicates trend values for frequency of "long-lived" tropical cyclones. Red indicates trend values for frequency of "long-lived" tropical cyclones after adjusting for estimated number of "missed" tropical cyclones using methodology of *VK08*. For example, at a threshold of 3.0 days, the trend for the short-lived TCs ($\leq$ 3.0 days) is +3.5 storms over the 1878-2008 period, the trend for long-lived TCs (> 3.0 days) is +0.5 storms over the 1878-2008 period, and the trend for long-lived TCs after adjusting for estimated number of "missed" TCs is -0.5 storms over the 1878-2008 period. Note that at the threshold of 0.0, all TCs are by definition "long-lived" and the "short-lived" TCs trend is zero (all TCs at that threshold are "long-lived").

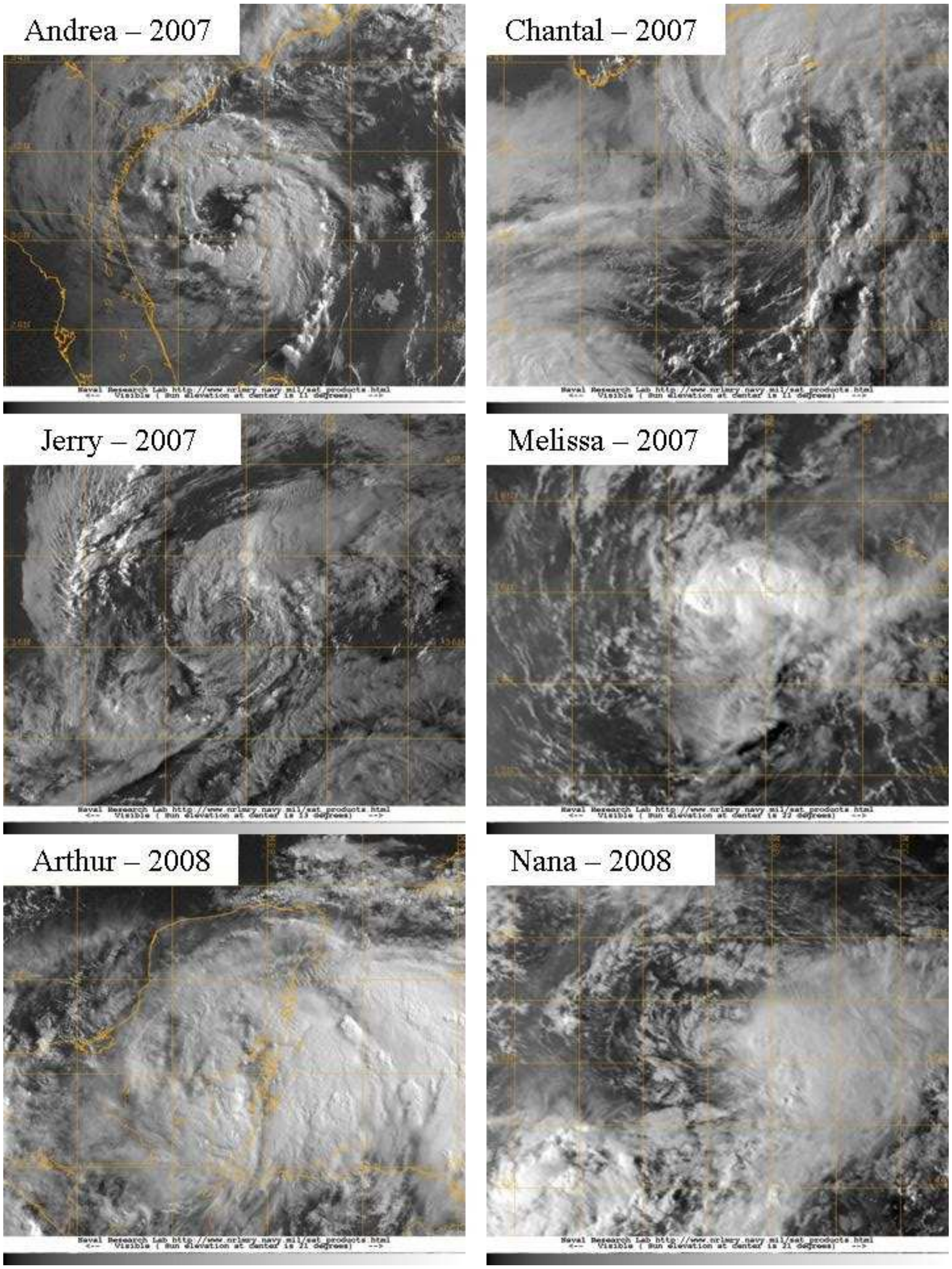

Figure 7: Six very short-lived, weak (average maximum intensity of 20.6 m/s) Atlantic basin tropical cyclones during 2007 and 2008 that were named (and included into HURDAT) likely because of newly available technology and analysis techniques. The visible imagery (courtesy of the Naval Research Laboratory) shows each cyclone at the time closest to their maximum intensity as a tropical cyclone.

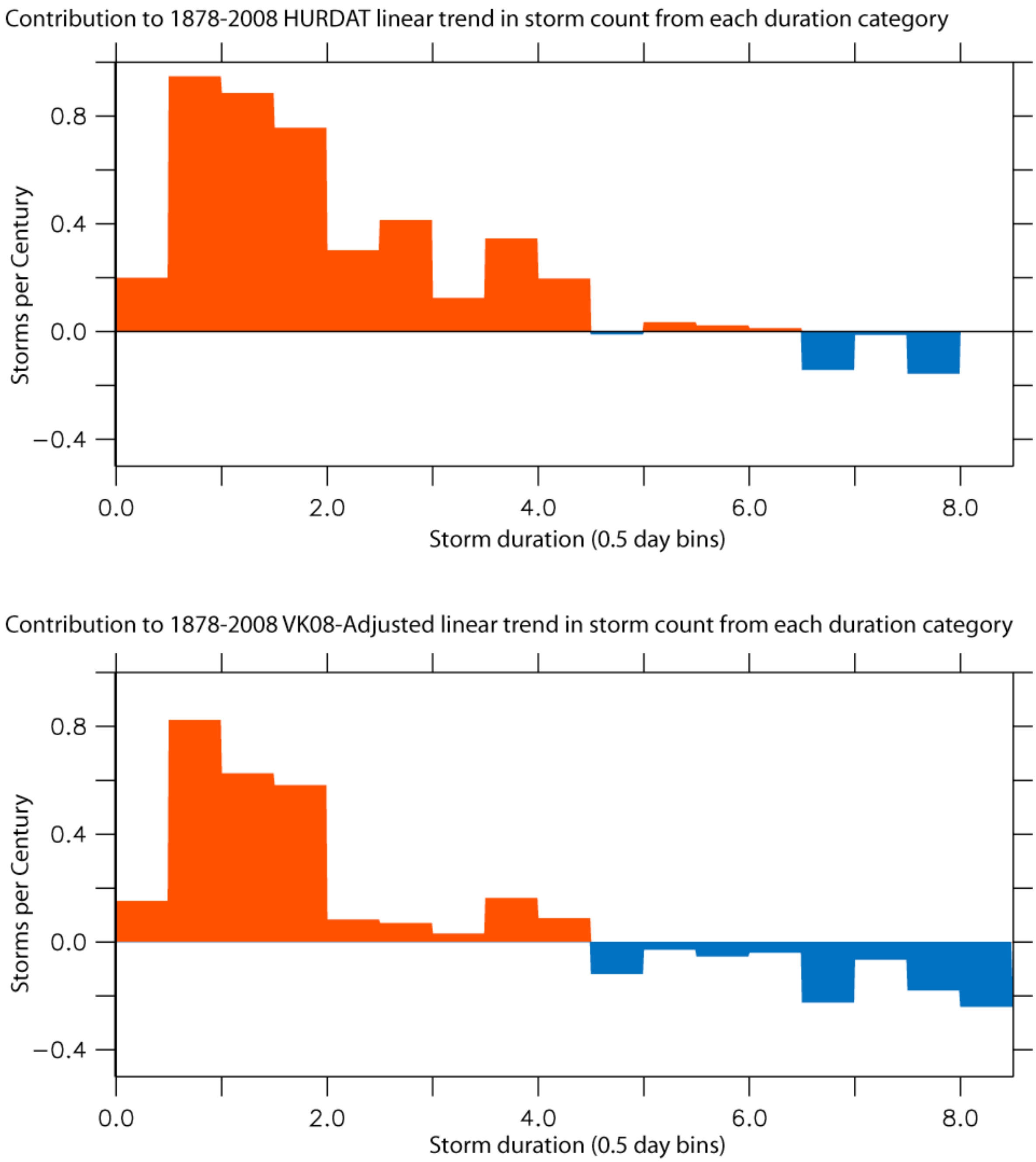

Figure A1: Contribution to the 1878-2008 linear trend in tropical storm counts from storms in each 0.5 day duration bin. Top panel is for the unadjusted HURDAT dataset, bottom panel is for the adjusted data using the methodology of *VK08*.

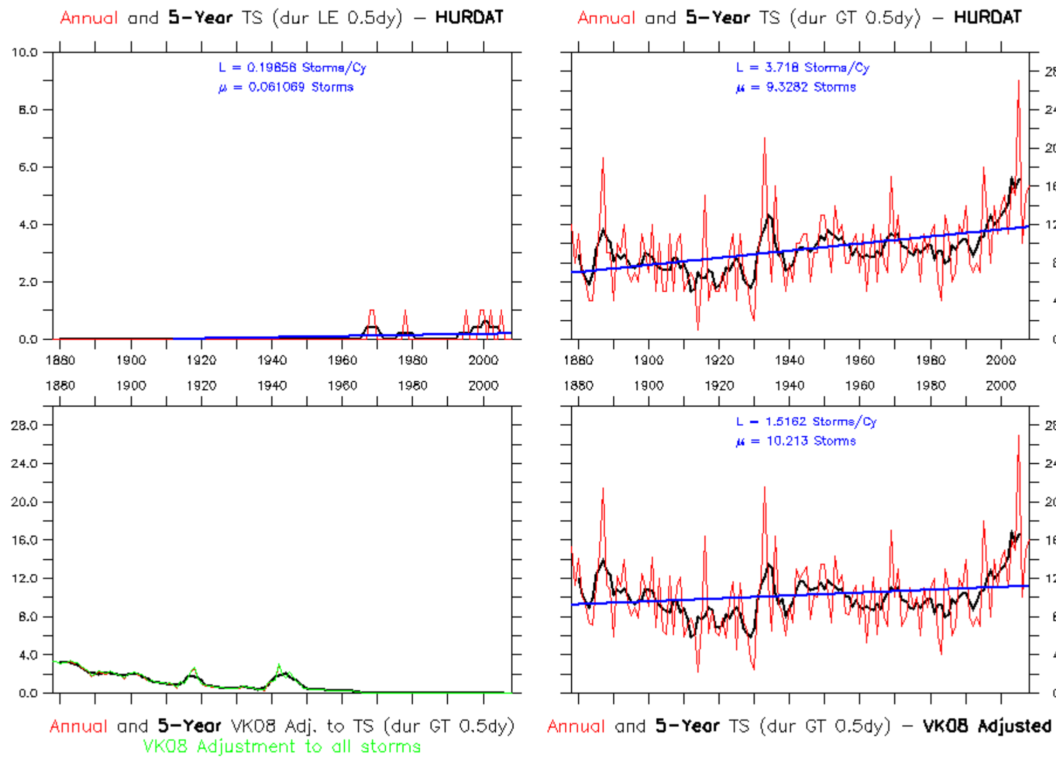

Figure A2: (upper left) Frequency (in red) of all Atlantic tropical cyclones (tropical and subtropical storms) which lasted as a tropical cyclone for 0.5 days or less from 1878 to 2008. (upper right) Frequency (in red) of Atlantic tropical cyclones that lasted greater than 0.5 days from 1878 to 2008. (bottom right) Adjusted frequency (in red) of Atlantic moderate to long-lived tropical cyclones from 1878 to 2008. For these three panels, the black curve is a five-year centered mean, and the blue line is the 1878 to 2008 trend. (bottom left) Estimated frequency (in red) of "missed" tropical cyclones of medium to long duration (greater than 0.5 days), "missed" storms estimated with the methodology of *VK08*. For the bottom left panel, the black curve is a five year centered mean. and the blue curve is the estimated frequency of "missed" tropical cyclones of any duration.

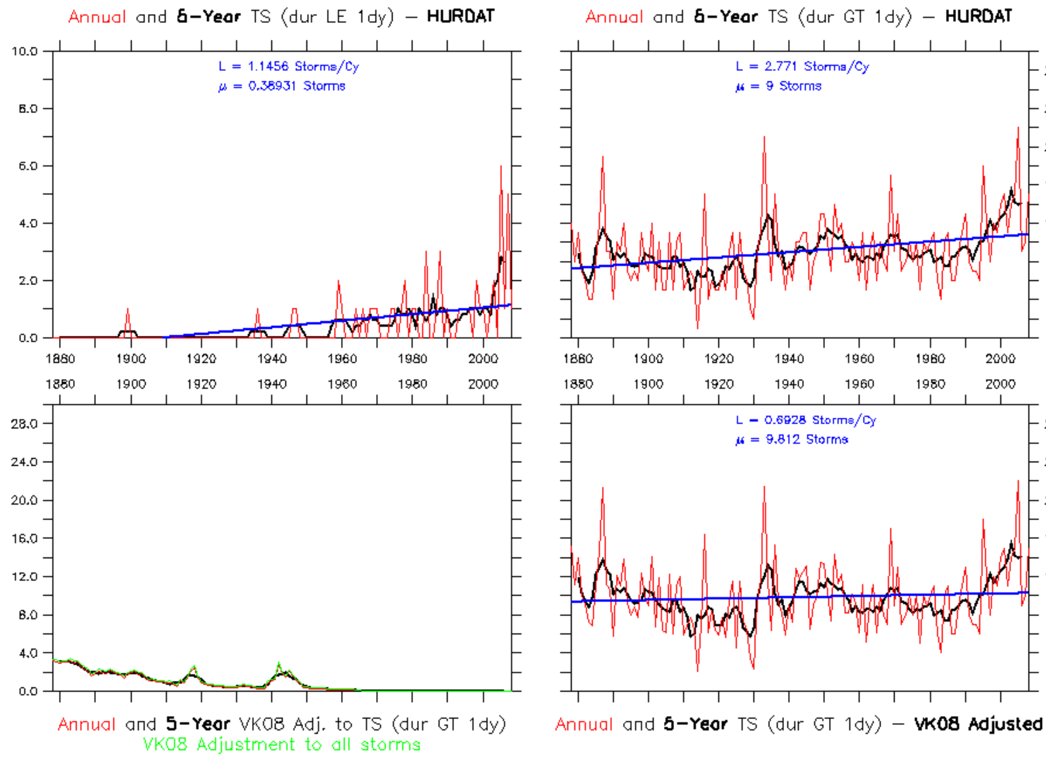

Figure A3: Same as Figure A2, but using a duration threshold for tropical cyclones of 1.0 days.

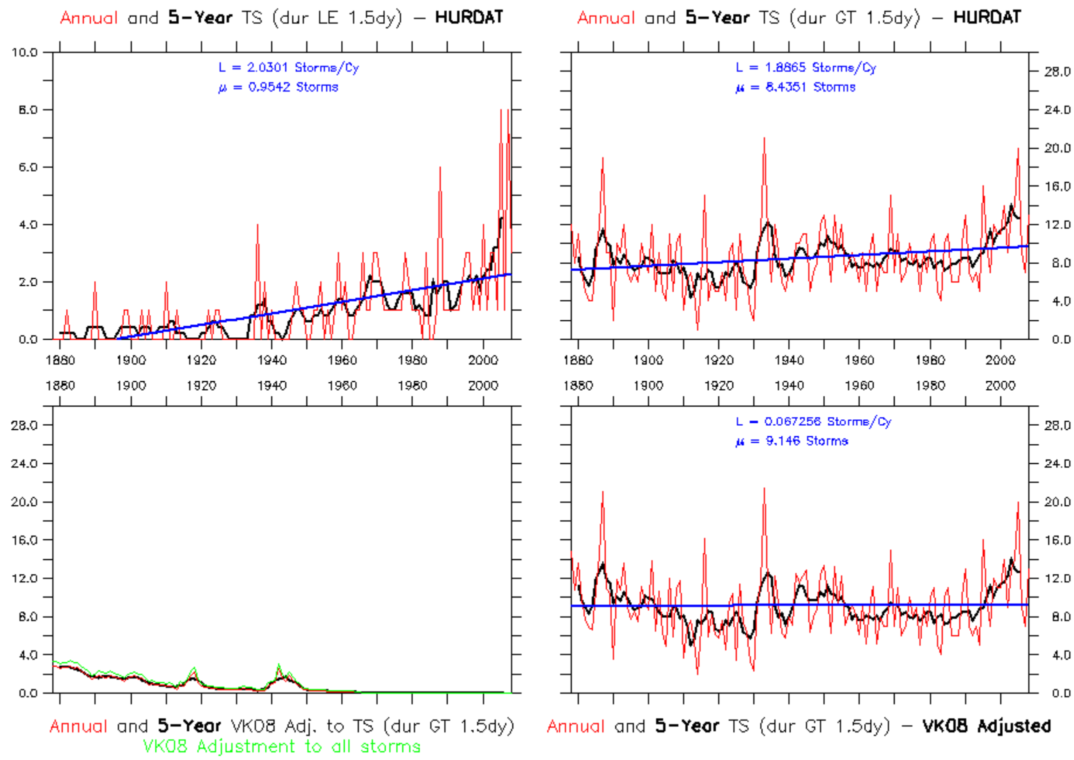

Figure A4: Same as Figure A2, but using a duration threshold for tropical cyclones of 1.5 days.

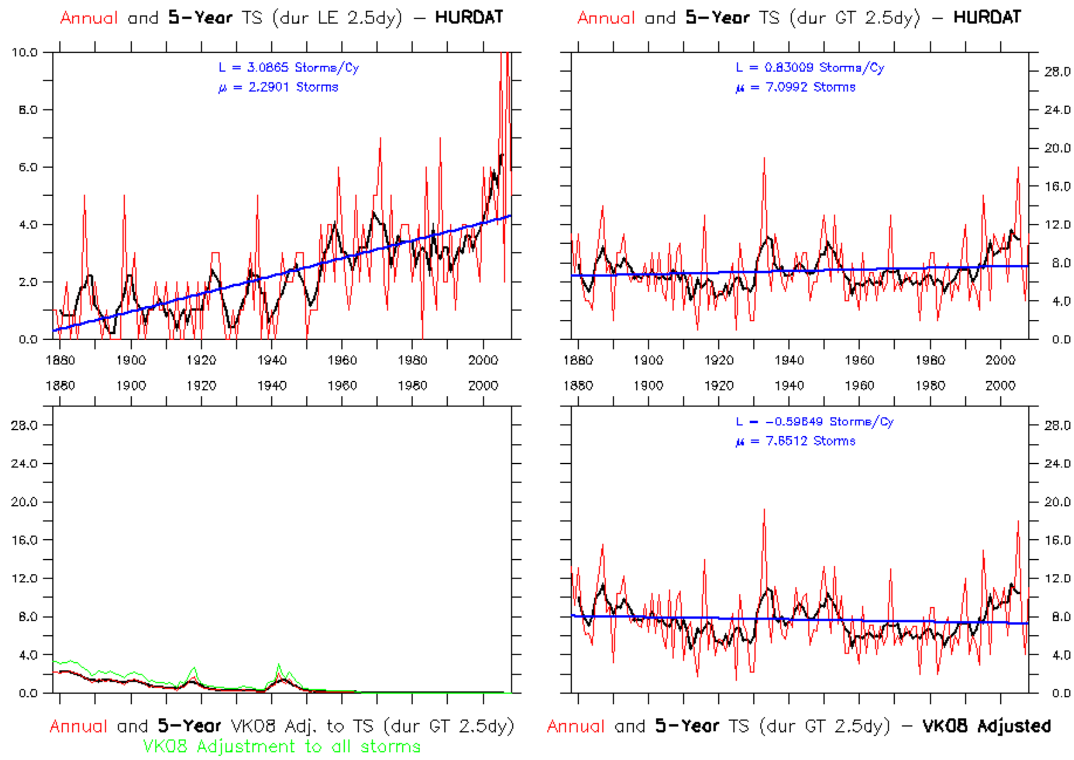

Figure A5: Same as Figure A2, but using a duration threshold for tropical cyclones of 2.5 days.

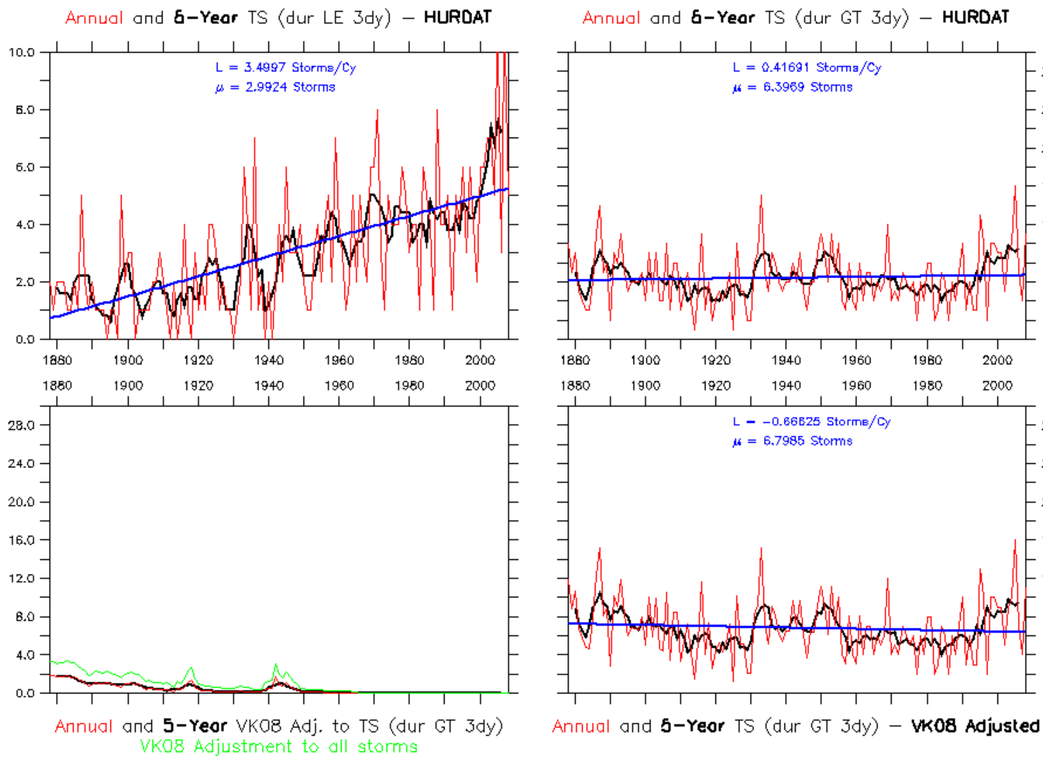

Figure A6: Same as Figure A2, but using a duration threshold for tropical cyclones of 3.0 days.

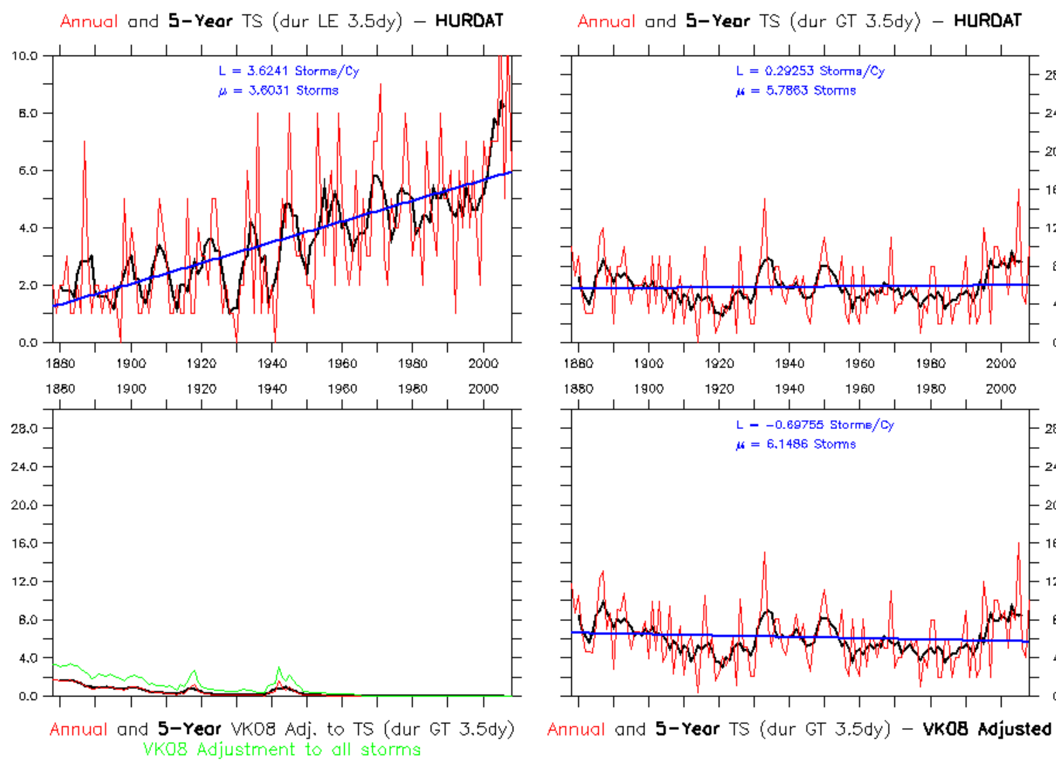

Figure A7: Same as Figure A2, but using a duration threshold for tropical cyclones of 3.5 days.

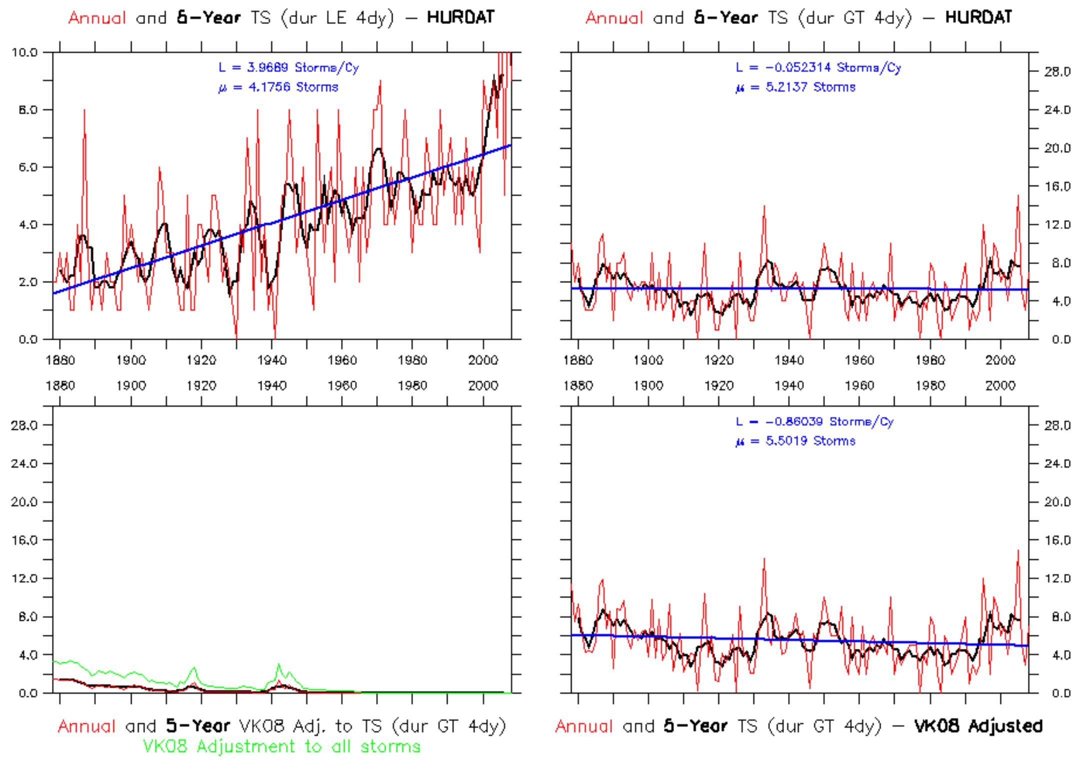

Figure A8: Same as Figure A2, but using a duration threshold for tropical cyclones of 4.0 days.

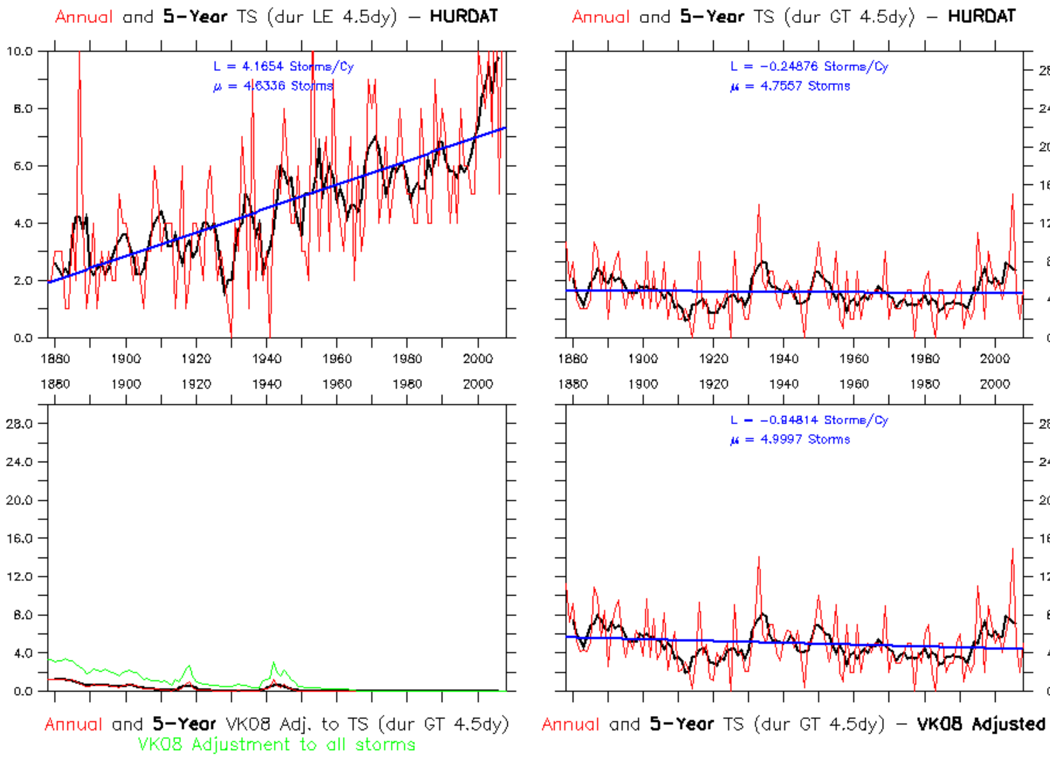

Figure A9: Same as Figure A2, but using a duration threshold for tropical cyclones of 4.5 days.

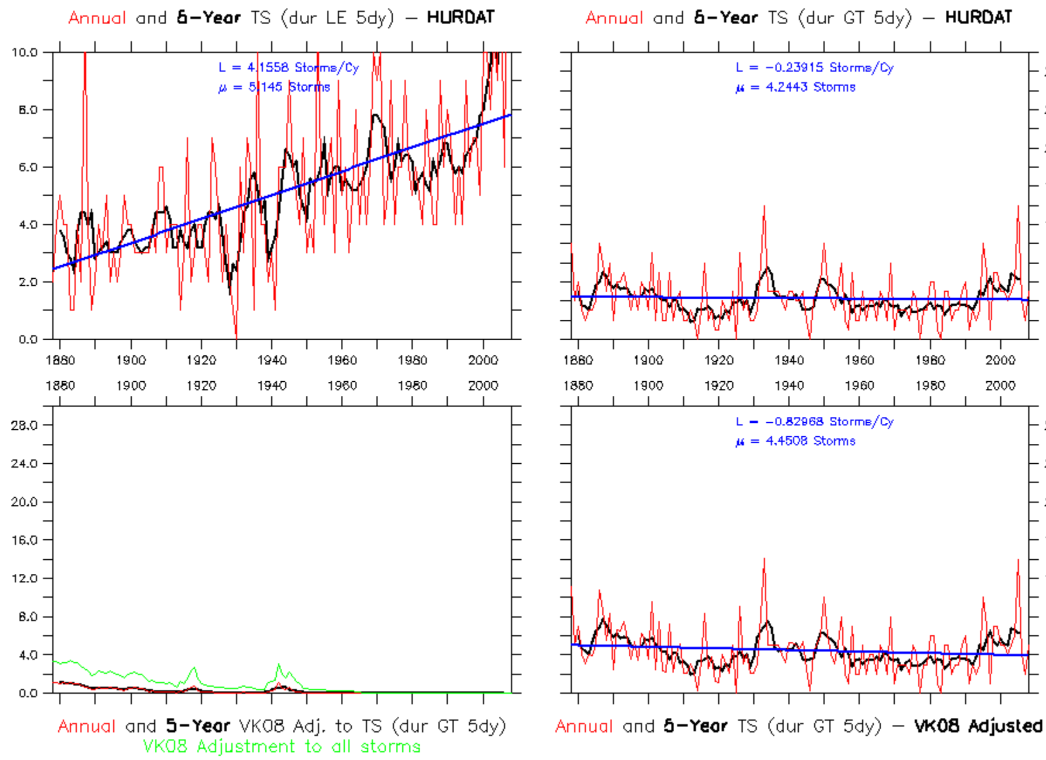

Figure A10: Same as Figure A2, but using a duration threshold for tropical cyclones of 5.0 days.

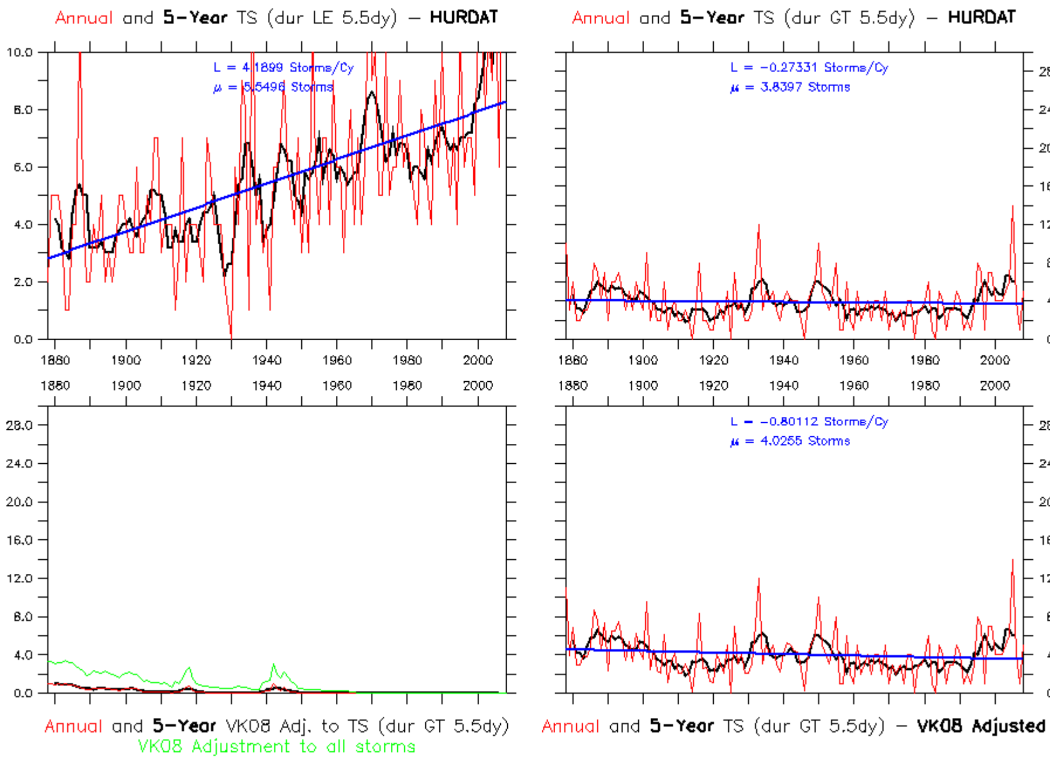

Figure A11: Same as Figure A2, but using a duration threshold for tropical cyclones of 5.5 days.

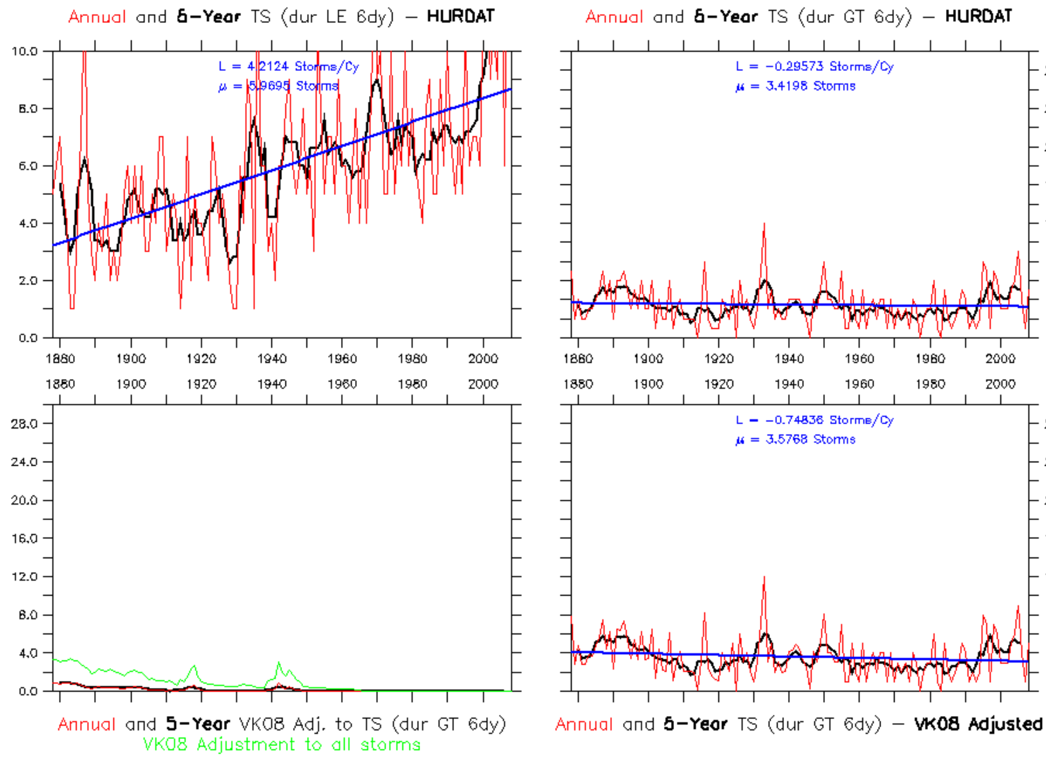

Figure A12: Same as Figure A2, but using a duration threshold for tropical cyclones of 6.0 days.

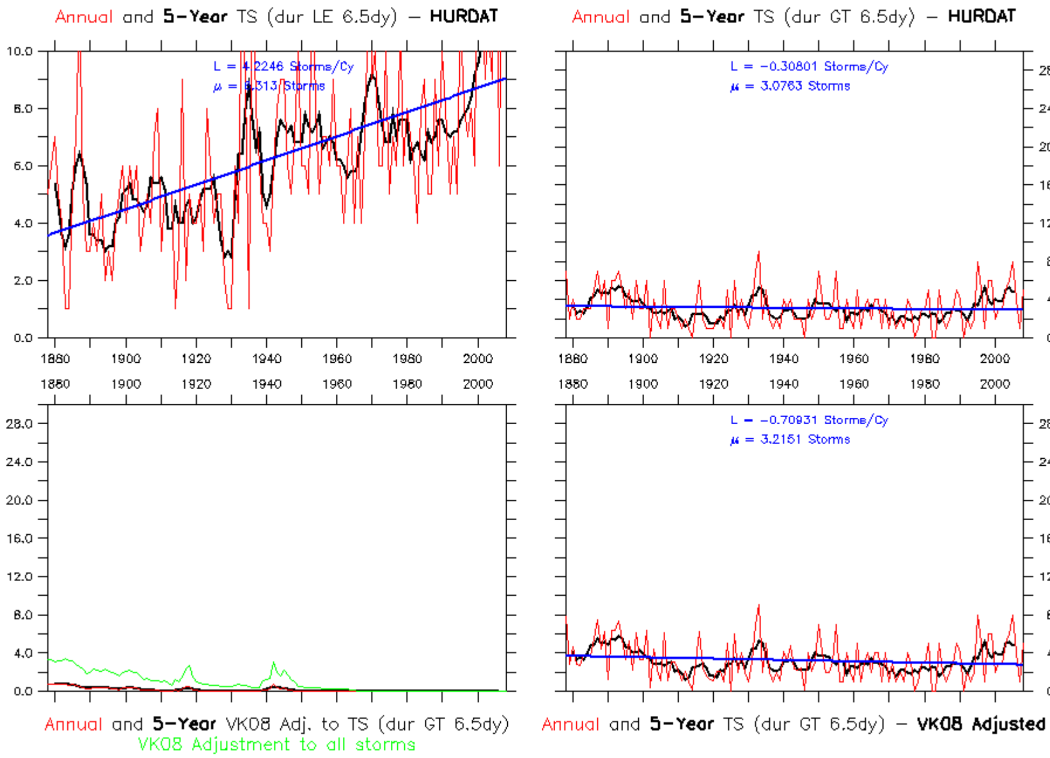

Figure A13: Same as Figure A2, but using a duration threshold for tropical cyclones of 6.5 days.

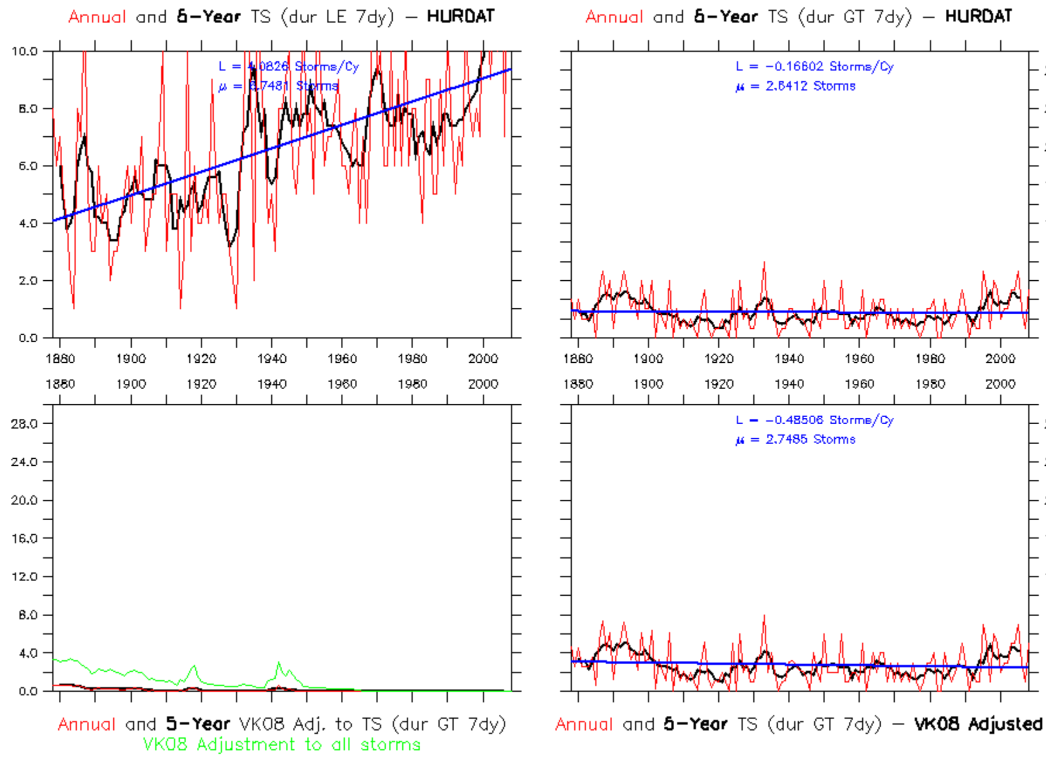

Figure A14: Same as Figure A2, but using a duration threshold for tropical cyclones of 7.0 days.

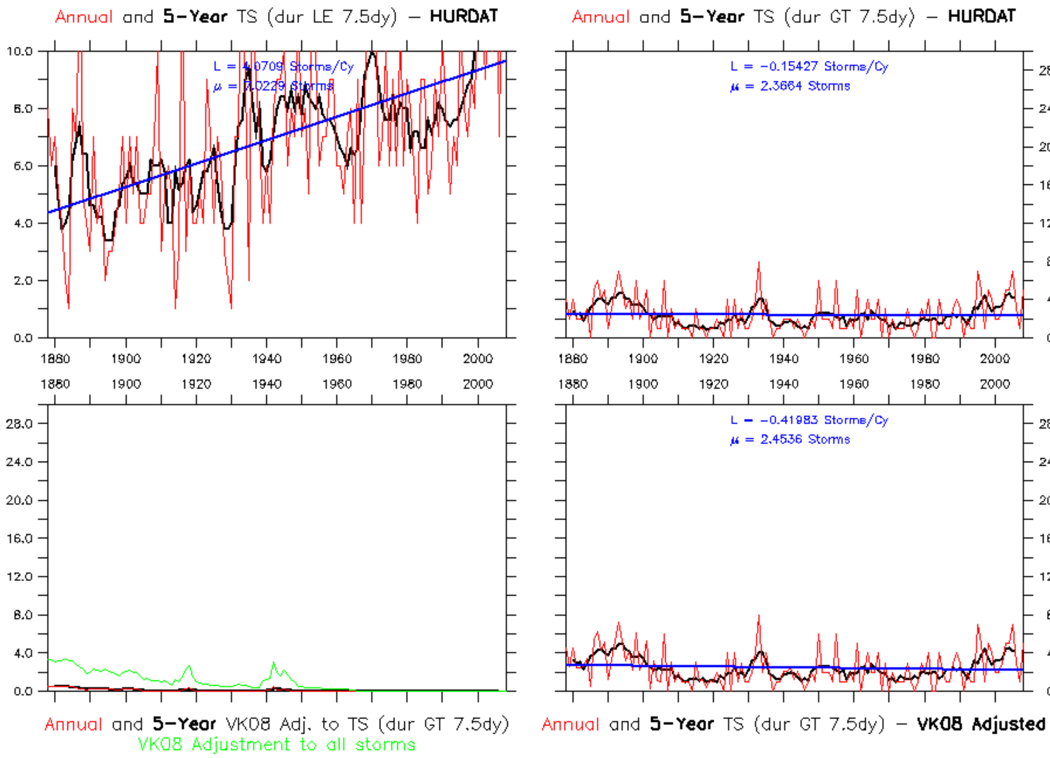

Figure A15: Same as Figure A2, but using a duration threshold for tropical cyclones of 7.5 days.

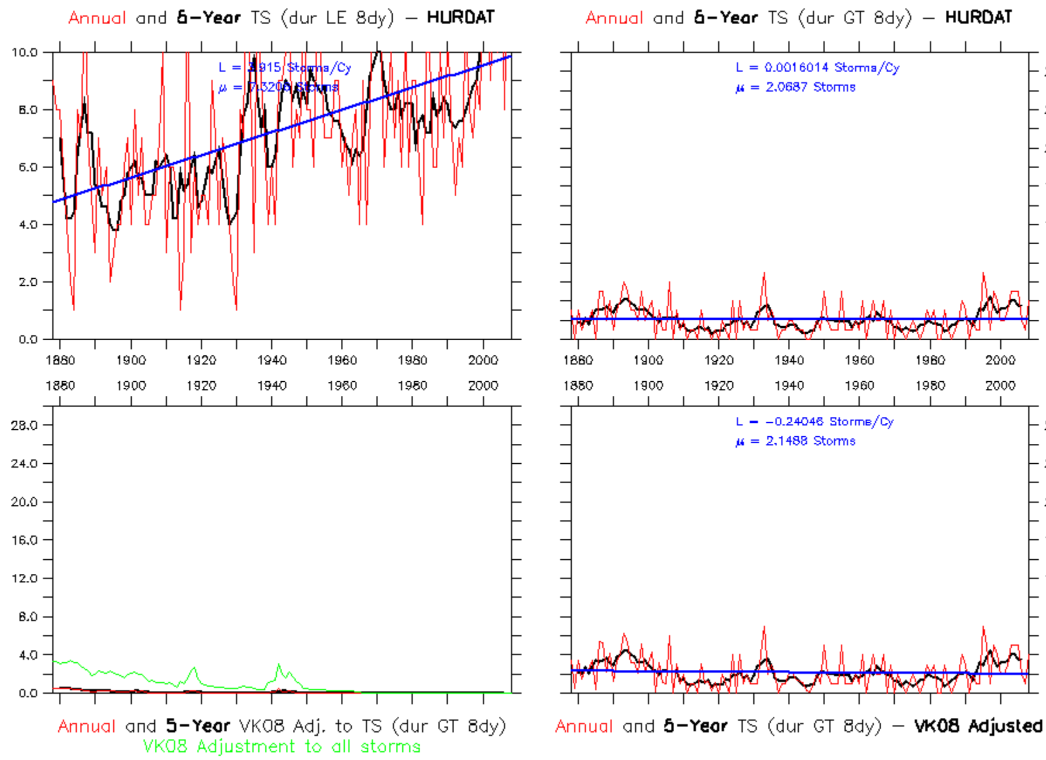

Figure A16: Same as Figure A2, but using a duration threshold for tropical cyclones of 8.0 days.

Table 1: Trend in tropical cyclone counts per year. Units are expressed in storms/year/century. Significance of trends is indicated as p-values in parenthesis next to the trend value; values significant at the *p*=0.05 level are highlighted in italic font. Significance computed using a Student's-t test on the timeseries of the square root of counts (Vecchi and Knutson 2008).

Type	1878-2008	1900-2008	1903-1994
Unadjusted, complete HURDAT	*3.92*	*5.81*	*3.16*
Very Short-Lived ($\leq$ 2.0 days) TCs	*2.79* ($<10^{-5}$)	*3.46* ($<10^{-5}$)	*3.12* ($<10^{-5}$)
Moderate to Long-Lived (> 2.0 days) TCs	1.13 (0.17)	*2.35 (0.02)*	0.04 (0.73)
Adjusted Moderate to Long-Lived TCs	-0.51 (0.60)	1.20 (0.27)	-1.18 (0.49)

Table 2: Median of Pair-wise Slopes (MPWS) of tropical cyclone counts per year. Units are expressed in storms/year/century. Significance of each MPWS is indicated as two-sided p-values in parenthesis next to the trend value; values significant at the *p*=0.05 level are highlighted in italic font. Significance computed is computed using a Spearman's rank test. See Lanzante (1996).

Type	1878-2008	1900-2008	1903-1994
Unadjusted, complete HURDAT	*3.45*	*5.25*	*2.69*
Very Short-Lived ($\leq$ 2.0 days) TCs	*2.17 ($<10^{-4}$)*	*2.86 ($<10^{-4}$)*	*2.52 ($<10^{-4}$)*
Moderate to Long-Lived (> 2.0 days) TCs	0.3 (0.10)	*1.78 (0.01)*	0.02 (0.55)
Adjusted Moderate to Long-Lived TCs	-0.45 (0.59)	0.60 (0.21)	-0.55 (0.64)